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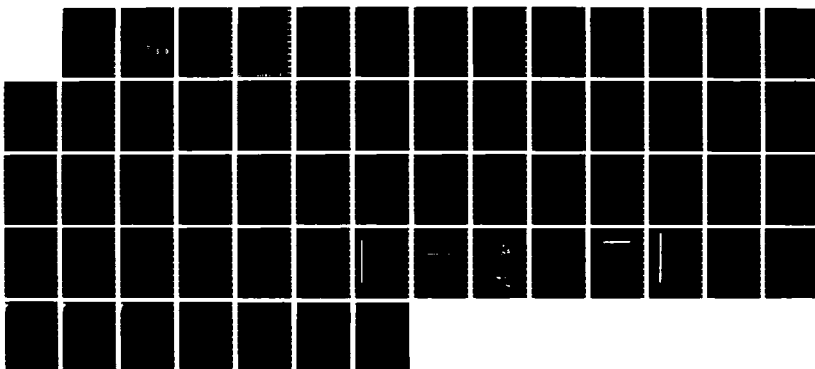
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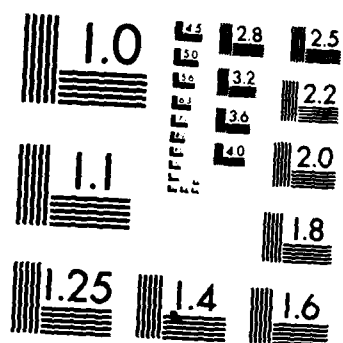
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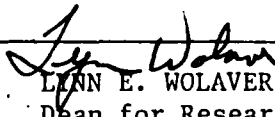
THE ROLE OF SYSTEM ARCHITECTURE
IN THE
STRATEGIC DEFENSE INITIATIVE

David M. Snyder
May 1986

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Independent Study Project, SE 799, conducted under the supervision of Dr. C. Nelson Dorny, Professor and Head, Department of Systems Engineering, School of Engineering and Applied Science, University of Pennsylvania.

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EXECUTIVE SUMMARY

President Reagan's Defense Initiative was unveiled over three years ago and has become one of this nation's most ambitious scientific undertakings. This vision of making nuclear weapons obsolete involves much more than just a scientific endeavor. It has become a subject of national debate and an issue of public policy and priorities. This report focuses on the preeminent role that the system architecture plays in continued research, development, and possible future deployment of a system. Individual components, weapons, and technologies are examined and the importance of the ability of these new technologies to integrate together into an effective technology portfolio is discussed. The technology portfolio must combine within the system architecture or framework. Key system architecture principles are enumerated and a discussion of true strategic defense proceed an attempt to outline a system architecture. This report concludes by amplifying the uncertainties that still exist in strategic defense research.

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GLOSSARY OF TERMS

ABM	- anti-ballistic missile
AI	- artificial intelligence
ASAT	- anti-satellite weapon
BM	- battle management
BMD	- ballistic missile defense
C	- command, control, and communications
counterforce	- attack strategy aimed at opponents attack capability
countervalue	- attack strategy aimed at opponents population and industrial capabilities
DEFCON	- Defense Conditions, U.S. alert status hierarchy
HOE	- Homing Overlay Experiment, the Army's 1984 missile interception test
ICBM	- Inter-continental Ballistic Missile
KKV	- kinetic kill vehicle
MAD	- Mutual Assured Destruction, nuclear deterrence strategy based on the ability of each side to absorb a nuclear first strike and retaliate with its' own strike
MIRV	- Multiple Independently Targeted Reentry Vehicle
MX	- Missile X, recently developed U.S. Peacekeeper ICBM
NASA	- National Aeronautics and Space Administration
RPV	- remotely piloted vehicle
RV	- reentry vehicle
SDI	- Strategic Defense Initiative
SDIO	- Strategic Defense Initiative Organization
SLBM	- Submarine Launched Ballistic Missile
Stealth	- very low radar signature technology for aircraft
VHSIC	- Very High Speed Integrated Circuits

PREFACE

This paper began as an examination the President's Strategic Defense Initiative (SDI) program in an effort to gain some insight into a systematic method for designing an architecture or framework for deploying large-scale, technologically sophisticated which involve the combination of many uncertain and unproven technologies. As the research progressed it became apparent that there are many unanswered questions regarding the architectural design of a theoretical SDI system. My research focused more on the specifics of the SDI system and how such a system might fit together. Throughout this paper I attempt to refrain from interjecting my opinions, or the opinions of others, as to the morality or the wisdom of investing in SDI research. My work begins with the assumption that it is national policy, as put forth by the President and approved by Congress through funding, that the U.S. should pursue research of the technologies associated with strategic defense. While the technical and economic feasibility of a deployable strategic defense system is the subject of much debate, my research is based on the premise; If SDI is feasible what should the architecture for such a system be like, what are the problems, and what are the key attributes?

I have restricted my sources to publicly accessible information obtained from the print media. Undoubtedly, there exists an extensive amount of classified information on the subject, which I had no access to. The Strategic Defense Initiative is a very timely topic and a great deal of new information is printed on SDI regularly, therefore the technical half-life of much of the information on which this report is based is relatively short. I consider my project as an "informed outsider's" attempt to design an architecture for a SDI system in which the component technical parts will fit.

I may have failed to live up to the ambitious undertaking outlined in my original research proposal, but I feel that I am in good company when it comes to not having many answers on how to develop a strategic defense system. We will probably all see the answers unfold as the years and possibly decades pass.

This project was conducted under the supervision of Dr. C. Nelson Dorny, Professor and Chairman, Department of Systems Engineering, as partial fulfillment of the requirements for the joint MBA/MSE degree at the University of Pennsylvania.

INTRODUCTION

In March of 1983 President Reagan publicly announced a comprehensive and intensive effort to define a long-term research and development program to investigate the feasibility of a system of defensive weapons to defend America against a nuclear attack. President Reagan called upon the scientific community to devise "the means of rendering these nuclear weapons impotent and obsolete."¹ The underlying concept focuses on a "smart" defensive system that relies on advanced technology sensors and non-nuclear weapons to destroy offensive ballistic missiles launched from enemy territory or from submarines. The fact that this concept conjures up the notion of an exotic spaced-based laser shield has earned it the name "Star Wars" in the popular press. While the precise structure of the Strategic Defense Initiative (the official name of this research program) is unknown at this time, a great deal of publicity and work has begun. Initially, a 50 member Presidential Commission headed by James C. Fletcher, the former Administrator of the National Aeronautics and Space Administration (NASA) who was recently reappointed to the top NASA post, was charged with setting the course for the Strategic Defense Initiative (SDI) research. In

1. President Ronald Reagan's televised speech, 23 March 1983.

late 1983, after the Fletcher commission recommended continued research into the feasibility of SDI, the Defense Department organized over 150 ongoing military technology projects under the umbrella of the newly created Strategic Defense Initiative Organization (SDIO) headed by USAF Lt. Gen. James Abrahamson with an initial 5-year budget of \$26 billion.² The program was divided into eight major system program offices: sensors; survivability, lethality, and key technologies; kinetic-energy weapons; directed energy weapons; innovative science and technology; resource management; and external affairs.

This Strategic Defense Initiative (SDI) not only represents a dramatic shift away from the U.S. nuclear deterrence strategy of Mutual Assured Destruction (MAD), but also poses a monumental technical challenge greater than that of the Manhattan project. There is a wide spectrum of technologies and disciplines which are being examined to determine their role in a SDI system. The individual technical obstacles are numerous, but even greater hurdles are presented by the integration of these diverse technologies into a robust and reliable system. This paper will examine the problem of assembling a diverse group of emerging technologies into a complex, large-scale system for defense against nuclear weapons. While many of the technologies discussed are specific to the SDI problem, the critical role

2. Ulsamer, "Charting a Course for SDI", Air Force Magazine, September 1984, p.108.

architecture plays in the development and deployment of sophisticated, technologically uncertain systems is evident. Principles derived from this systems approach to strategic defense carry an underlying theme that can be transferred to similar massive interdisciplinary development programs. This report will conclude with a general description of features that are likely to be found in the strategic defense architecture. Development of an overall system architecture is the key in deploying an efficient system should individual technologies prove to be effective. However, the design of the architecture must be influenced by what technologies appear to be most promising.

SYSTEM ARCHITECTURE

The most critical element in the SDI problem, or any large-scale system, is the system architecture. The system architecture is the framework or skeleton on which the component technologies are incrementally placed. The architecture is the common bond which provides the continuity between different technical solutions to various mission tasks and integrates the component tasks into one unified system. Once the architecture is in place, component technologies can be added, replaced, altered, expanded, and improved, but the basic structure remains intact. This places paramount importance in formulating an

effective architecture that can accommodate many technical uncertainties and changes. The greater the technical uncertainties the greater the importance of the system architecture. The SDI research certainly abounds with technical uncertainties.

There have been several SDI architectural studies accomplished already with the Pentagon's internal Strategic Defense Architecture (SDA-2000) study serving as a long-term roadmap to integrate air, space, and ballistic missile defense.³ Additionally, six contractors participated in a six-month Phase I architectural study of spaced-based battle management/command and control for ballistic missile defense in a program managed at the Electronic Systems Division of the Air Force Systems Command.⁴ Three of these contractors were awarded contracts for the second phase of architectural studies that will lead to requests for proposals for the development of a SDI architecture. Separately, the SDIO is studying the requirement for a national test facility for large-scale simulation experiments. The high priority that is being placed on the overall strategic defense architecture is apparent. A successful architecture will divide the unwieldy problem of strategic defense into manageable component problems

3. Ulsamer, "The Battle for SDI", Air Force Magazine, February 1985, p. 45.

4. Gregory, Aviation Week and Space Technology, March 31, 1986, p. 16.

that can be incrementally solved. The architecture must be capable of accommodating the set or portfolio of technologies as technologies develop and capabilities expand.

TECHNOLOGY PORTFOLIO

The portfolio model of technological development is based on the concept that a sophisticated, high-technology system such as a SDI system is developed and operated under a myriad of constraints and tradeoffs. As individual component technologies evolve or advance the tradeoffs become more pronounced. For example, as missile tracking technology improves, more and faster tracking data is possible and both computing power and intercept weapon tracking must accommodate these higher tracking speeds. The increase in computing power required for faster tracking necessitates larger computing capability, in turn resulting in heavier space-borne power sources. As technology removes technical constraints and pushes the performance frontier of one parameter out further, new constraints are imposed often on a different parameter. The portfolio approach concludes that a technical system will be composed of a collection of individual technologies that combine together to make the most effective total system. This may often mean returning to a mature technology for one component of the total system because of the impact that it has on other components of the system. It may

also imply that as related technologies diffuse or advance in regard to one parameter, an opportunity may avail itself to use a previously abandoned technology in another component of the system. The system architecture must accommodate technological changes as the total system portfolio of technologies shifts.

A very important consideration in the development of an architecture for massive technology intensive systems is how technological changes will affect the portfolio of technologies. This consideration is foremost in the development of a SDI architecture and necessitates an incremental build-up of subsystems and component technologies in a phased or modular approach with possible upgrades of components considered in follow-on development.

THE STRATEGIC DEFENSE CONCEPT

The SDI concept is a controversial topic that is one of the favorite topics of the popular media and as such there is a fair amount of misunderstanding as to what "Star Wars" actually is. In order to understand the complex architecture problem associated with strategic defense an understanding of what is being attempted with the SDI is essential.

The Strategic Defense Initiative is a research and development program to determine if an effective, reliable defense against

nuclear ballistic missiles can be built, the degree of protection in might provide, and how much it might cost.⁵ The immediate goal of the SDI is to conduct research on the technologies required to intercept ballistic missiles after they have been launched to prevent them from reaching their targets. Over the long term, SDI is to look for the means of defending specific military targets as well as civilian populations, both in the U.S. and in allied countries. Edgar Ulsamer, Air Force Magazine's Senior Editor characterizes the tasks of a strategic defense system as follows:

Three distinct "echelons" of ballistic missile defense are implied by the SDI mission. Obviously central - and probably the most "doable" in a technical and operational sense - is defense against a counterforce attack. Such a defense need not be totally "leakproof" to be militarily effective. If such a defense is perceived by the attacker as denying him his military objectives, the utility of a preemptive nuclear strike is thwarted and strategic stability strengthened. If the attacker is forced to expend the lion's share of his ballistic missile arsenal to destroy a handful of the other side's ICBM, even a latter-day Attila the Hun will presumably be deterred. The second echelon of defense - protection of industrial, transportation, and other types of targets required to sustain war fighting efforts - poses a somewhat tougher problem. Under these conditions, the defenses need to be denser and more leakproof. In the last instance, protection of the civilian population, the task of the defense becomes herculean, and the defense must be essentially leakproof since only a few weapons getting through would equate to millions of casualties. The purpose of the initial phase of the SDI program is to establish whether - and how soon - these various levels of

5. "Ballistic Missile Defense", Issues in Science and Technology, Fall 1984, p. 13.

defensive capabilities can be attained.⁶

The sheer size of this final "leak proof" echelon of the strategic defense mission is shown by the calculations in Figure 1. These calculations show that an all out Soviet attack of 1400 MX type (MIRVed) rockets launched with 10 warheads per missile and 10 decoys per warhead results in 154,000 objects (14,000 warheads and 140,000 decoys) to be identified, tracked, discriminated, and intercepted if lethal. This must be accomplished within the 30 minute maximum flight time of an ICBM. To prevent large scale loss of life, not one single warhead can penetrate the SDI shield. Much debate centers on the ability of a strategic defense to ever be up to this task.

Deputy Secretary of Defense William H. Taft IV focuses on a narrower goal for SDI research when he stated that to "prove the potential of a defensive deterrent, the first goal of SDI research, we need only show that we can make the success of any attack so uncertain that an adversary would not hazard aggression".⁷ This is a fundamental shift in the present national strategy of offensive deterrence or Mutual Assured Destruction (MAD) which evolved in the sixties. The Mutual Assured Destruction strategy calls on the U.S. to absorb a Soviet

6. Ulsamer, "Charting a Course for SDI", Air Force Magazine, September 1984, p. 108.

7. "The Battle for SDI, Air Force Magazine, February 1985, p. 45.

first strike against our triad of nuclear forces (ICBMs, manned strategic bombers, and submarine launched ballistic missiles or SLBMs) and then launch our own retaliatory attack, possibly against Soviet cities. The hardening and diversification of nuclear launch vehicles was an important element of the MAD strategy.

Technological advances are rapidly altering the calculus of MAD. Improved guidance systems enable the accurate delivery of throw weights sufficient to knock out even the most hardened locations. Missile accuracy is improving so much that the explosive power of warheads needed to penetrate hardened silos is decreasing. In fact, the megatonnage of the U.S. arsenal has decreased by 60 percent over the last two decades and research is being conducted into the use of conventional warheads to replace some counterforce-targeted, nuclear warheads.⁸ The use of multiple independently targeted reentry vehicles (MIRVs) allow one missile to be targeted against several separate locations. The unratified SALT II treaty limits each missile to 10 warheads, but this still greatly complicates the ability of the attacked country to withstand a first strike. Additionally, the potential deployment of small, single, mobile, highly accurate "Midgetman" ICBMs which are more widely dispersed is an attempt to shore up the MAD strategy.

8. Meinel, "Fighting MAD", Technology Review, April 1984, p. 34.

It is apparent that strategy has not kept up with technology and the strategic defense research is an attempt to determine if new technological developments make a defensive deterrence strategy feasible and cost effective. Whether one believes that such a shield must be leakproof or must only generate sufficient uncertainty in the minds of the attackers to act as a deterrent, the strategic defense must initially be capable of ballistic missile interception. Figure 2 lists fifteen of the major SDI experiments currently underway.⁹

BALLISTIC MISSILE DEFENSE

Ballistic missile defense is the central theme of SDI research. Current concepts call for the division of the missile interception into four generally distinct phases; boost phase, post-boost phase, midcourse phase, and terminal phase. The approximate flight time that a missile spends in each phase is shown in Figure 3. The SDI approach relies on a layered defense, each layer relating to one phase of a fired missile requiring distinct technical and operational capabilities to deal with each of these phases. Each phase of missile flight presents advantages and disadvantages to the defense planner.

9. "SDI: The Grand Experiment", IEEE Spectrum, September 1985, p.57.

In the first phase or boost phase the missile is launched from the silo and ascends through the atmosphere. The rocket engines of the missiles first three stages burn brightly and generate an unambiguous "signature" easily detectable with infrared sensors. In the second or post-boost phase the "bus" separates from the main rocket boosters, and the warheads or multiple re-entry vehicles (RVs) along with any penetration aids or decoys are deployed. The third and longest phase is the midcourse phase. During this phase the RVs and penetration aids travel on a ballistic trajectory outside of the atmosphere. The final or terminal phase occurs when the warheads and penetration aids reenter the earth's atmosphere. Figure 4 offers a graphic representation of the different phases of a ballistic missile launch.

The boost phase provides the best opportunity for interception of a ballistic missile because it is easy to identify and because the "bus" is still intact making the target lucrative. Neither the penetration aids nor the individual warheads have been deployed and the defense system is assured of destroying all the warheads if interception occurs during the boost phase. Presently, there is sufficient time for detecting, tracking, and intercepting the missile during the approximately 3 minutes of rocket burn. Large Soviet ICBMs and SLBMS are relatively slow. In fact, the SS-18 has a five minute boost burn. The possibility of fast burn missiles presents a threat to boost phase interception. The fastest burning missile is the U.S. MX which

has a burn time of 150 seconds. Experts speculate that the next generation of Soviet missiles may be able to achieve burn times as low as 50 seconds and have a "cold launch" capability which ejects the missile from the silo prior to ignition so that the silo is not damaged and can be reloaded. A simultaneous full-scale missile attack requires a large number of intercept weapons and the ability to retarget extremely rapidly. However, General Abrahamson, the SDI Director, indicates that there is no evidence that the burn time can be cut to a point where there is no adequate "window" for intercepts by the defense during the ballistic missile boost phase.¹⁰

Once the final stage of the rocket motor burns out, the missile enters the second or post-boost phase where the post-boost vehicle, or "bus", maneuvers through space powered by a low thrust rocket and drops off its reentry vehicles and penetration aids in a programmed sequence, sending them on their distinct trajectories. This sequence requires 5 to 8 minutes. The advantage to attacking early in the post-boost phase is that it may be possible to intercept the bus before it deploys most of its decoys and warheads. However, the colder flame of the bus's low thrust engine is more difficult to detect and the maneuvering bus may be hardened to withstand attacks by some types of weapons.

10. Ulsamer, "Charting a Course for SDI", Air Force Magazine, September 1984, p. 108.

The midcourse phase begins when the RVs and penetration aids are released and they begin their ballistic trajectory in a unguided ascent to an apogee of 1,200 kilometers and descent back into the atmosphere. The midcourse phase offers the defenders the advantage of a long 20-25 minute engagement time with a predictable freefall ballistic trajectory. The disadvantage in midcourse interceptions is that the decoys and penetration aids have been deployed making discrimination of the warheads difficult. Additionally, warheads are hardened to withstand reentry further complicating interception.

The terminal phase begins when the RVs, penetration aids, decoys, and debris begin to reenter the upper atmosphere at about 100 kilometers above the earth's surface. The warheads are heat shielded and aerodynamically shaped so that they will survive reentry intact. The lightweight objects, including most decoys burn up on reentry. The terminal phase can be as long as two minutes and the warheads are relatively easy to identify and track because of their hot glow from reentry. However, the time for interception is short and the terminal phase is the last chance for the defenses to act, implying that they must be virtually leakproof. Terminal phase missile defense was the concept behind the anti-ballistic missile (ABM) system that the U.S. developed, deployed and disbanded in the early seventies. The Soviets currently have an operational ABM system deployed around Moscow.

The layered approach to ballistic missile defense or "defense-in-depth" concept relies on a series of moderately effective layers that back each other up and combine to produce a highly effective total system defense. As shown in Figure 1, if all four layers are each 90% effective the total system would be 99.99%, while if each layer were only 70% effective the total system is still greater than 99% effective. Additionally, the multilayered approach to ballistic missile defense complicates the ability of the attacker to use countermeasures that will fool the variety of different sensors and weapons used in the different layers. For example, if the attacker increases the hardening of its warheads it must pay a price for the increased weight. This means either fewer warheads or fewer decoys and penetration aids can be launched on each missile.

ESSENTIAL TASKS OF BALLISTIC MISSILE DEFENSE

An effective ballistic missile defense system must perform certain essential functions in each phase. These tasks are surveillance, acquisition, and discrimination; pointing and tracking; target interception; and battle management.¹¹ These tasks should not necessarily be performed independently among one

11. Fletcher, "The Technologies for Ballistic Missile Defense", Issues in Science and Technology, Fall 1984, p. 18.

phase or between phases, but must be an integrated solution that breaks the complex problem of BMD into manageable components.

Surveillance and acquisition involves vigilant search around protected areas and/or launch areas to detect any potential threat and determine the intensity, initial trajectory and destination/target of the attack. Discrimination involves the interpretation of acquisition data to identify the threat as either a lethal warhead or a non-lethal decoy. Additionally, discrimination should include the ability to determine if a threat has been successfully destroyed.

Pointing and tracking is the determination of the velocity of each threat to determine its future flight path. This data is used to guide the interception weapon to the threat.

Target intercept and destruction is the use of any one of a number of weapons to destroy the incoming lethal threat. Information on the successful destruction of a booster or RV must be accurately determined so that intercept resources are not allocated to repeat an already accomplished interception.

Battle management is one of the most difficult and complex tasks in the strategic defense concept. It encompasses all the data management, command, control, communications, verification and decision making functions necessary to coordinate the defensive action.

STRATEGIC DEFENSE INITIATIVE COMPONENTS, WEAPONS, AND TECHNOLOGIES

COMPONENTS

In order to accomplish the task of ballistic missile defense a variety of components must be integrated together. While there are several proposed systems for combining components, the exact makeup of any system has not been determined. It is too early to know which components will prove to be the most effective or how a system might be configured from them. Dr Fletcher offers his idea of likely components for a ballistic missile defense as shown in Figure 5.¹² He envisions sensor satellites in geosynchronous orbit to detect missiles in all phases of flight. These satellites contain infrared sensors which detect the thermal radiation of an object and on-board, rocket-powered interceptors to protect themselves from anti-satellite weapons. The sensors would continuously scan designated areas from their stationary position relative to the earth. These sensors would be capable of detecting a launch, determining the nature and

12. Fletcher, "The Technologies for Ballistic Missile Defense", Issues in Science and Technology, Fall 1984, p. 20.

destination of the attack, and updating the trajectory. This information would be passed to the boost phase battle stations and to an array of midcourse sensors in low earth orbit. These battle stations would be laser weapons, particle beam platforms, hypervelocity guns, rocket pod platforms or a combination of all or several weapons.

Dr. Fletcher sees particular promise in the use of hypervelocity guns which shoot "smart bullets", named so for their ability to maneuver during the last few kilometers of interception guided by internal homing devices. Researchers hope these kinetic energy weapons will propel a bullet at speeds up to 30 km/sec with sufficient energy to destroy a missile.

The initial data from the geosynchronous sensors would be passed on to the low earth orbit sensors that update the data as the warheads and decoys leave the bus on their individual trajectory during the post-boost and midcourse phase. The hypervelocity guns would be redirected with the updated information provided from the increasing number and variety of sensing and imaging devices on the satellites. In the midcourse phase the target discrimination process would begin. Space-borne scanners that operate at many different wavelengths including radar, optical, and inferred sensors detect unique signatures from the warheads, debris, and penetration aids (balloons, chaff, and decoys). To aid in the discrimination task moderate energy lasers on the ground or in space scan large sections of the

engagement area illuminating hundreds of objects and observing the characteristic of the reflected energy to determine weight, size, temperature, and density of the object. Warheads will have distinguishing features that decoys do not have because of the weight differences necessitated by the throw weight limitations of the missiles.

In Dr. Fletcher's hypothetical defense system, thousands of small ground based chemical rockets are fired in the direction of identified warhead targets. As the rockets near the warheads they fire their non-nuclear projectiles or "smart bullets" and destroy the warheads before they enter the atmosphere. Additionally, uncommitted space-based weapons are brought to bear on the warheads.

In the terminal phase of the warhead trajectory all objects that reenter the atmosphere are tracked by infrared sensors aboard high-altitude aircraft that are launched on warning of attack or in constant air alert. The airborne sensors use data obtained from previous tracking methods and work in conjunction with ground-based radar. The terminal phase interception is carried out by ground-based, high-acceleration chemical rockets. These rockets carry non-nuclear defensive warheads that explode when they near the incoming warhead scattering a cloud of shrapnel in the path of the warhead destroying it. These interceptors attempt to intercept incoming warheads as high as possible in the atmosphere to prevent damage from detonation of

the incoming nuclear weapon.

The most important component of this or any system is the battle management(BM) system which coordinates the command, control, and communications (C³) of the entire system through a network of high-speed, high-capacity computers located in space and on the ground. Dr. Fletcher describes the battle management system as follows:

This System provides the communications link between the myriad components of the defense. It performs the data processing, or analysis, necessary to identify targets and support operations...Each defensive layer has its own semi-autonomous battle management system, composed of its sensors, weapons, and data-processing equipment that monitors the global situation, allocates the defensive weapons, directs their fire, and records the results of each attempted intercept. The battle management systems in each phase are interconnected, allowing for redundant, decentralized command and control of the entire defensive effort. The overall system maintains a master file that provides birth-to-death tracking of every potentially threatening object - the hundreds of thousands of warheads, decoys, penetration aids, and pieces of debris. This system provides global summaries of the progress of battle and in most cases replaces human decision making.¹³

This strategic defense system described by Dr. Fletcher is a hypothetical system based on concepts currently prevalent in SDI research. There are a variety of alternate or supplemental weapons and concepts being considered. Figure 6 lists the possible defensive weapons used in each phase of a ballistic

13. Fletcher, "The Technologies for Ballistic Missile Defense", Issues in Science and Technology, Fall 1984, p. 21.

missile defense and outlines some of the countermeasures used to defeat these weapons, as well as counter-countermeasures.¹⁴

STRATEGIC DEFENSE WEAPONS

A brief review of some of the specific weapon systems undergoing research for possible SDI applications will provide a better understanding of the difficulties faced. Figure 7 depicts the strengths and weaknesses of currently considered weapons.¹⁵ Both space-based and ground-based weapons are being considered. The major advantage of ground-based weapons is that large heavy power sources can be used to power them, where weight is a limiting factor for spaced-based weapons. Conceptual diagrams of the different weapons are shown in Figures 8 and 9.¹⁶

Lasers provide several options for destructive weapons. Although the atmosphere effectively blocks many of the wavelengths employed by lasers, there are certain narrow windows of wavelengths at which the laser energy will pass. However,

14. "SDI: The Grand Experiment", IEEE Spectrum, September 1985, p.48.

15. "SDI: The Grand Experiment", IEEE Spectrum, September 1985, p.49.

16. "Battlegrounds in the Heavens", Discover, September 1985, pp. 43-61.

these wavelengths are difficult to achieve with most lasers. Chemical lasers offer the most mature technology, but the key problem at present is that the wavelengths used by chemical laser beams is in the 1-4 micrometer range, while 0.3-1 micrometer wavelengths transmit most effectively. The brightest laser outside of the Soviet Union is a hydrogen fluoride laser called Miracl (mid-infrared advanced chemical laser) which transmits on the 2.7 micrometer wavelength and requires 2.2 megawatts of power.¹⁷ Oxygen-pumped iodine lasers lase at 1.3 micrometers. The light would be amplified and aimed by a system of mirrors, aided by a new technology called adaptive optics (see Figure 8), in which small, thin reflectors are individually adjusted.

Free-electron lasers, which can be individually tuned to radiate at any wavelength in the 0.1-20 range, depend on fast moving electrons that give off light as they are agitated violently while passing through "wiggler" magnets. However, these free-electron lasers require large electric power sources and have an efficiency of only 2 to 3 percent.

The excimer (for excited dimer laser) uses an electric discharge to "excite" molecules of gases into forming unstable compounds that give off light as they break down. The current state of technology of these lasers is also hampered by the

17. "SDI: The Grand Experiment", IEEE Spectrum, September 1985, p.49.

inefficient use of power.

The use of X-ray lasers, which were until recently considered unlikely candidates for SDI weapons, is part of a concept developed by Edward Teller called the "pop-up" defense. The laser is contained in a canister that is launched on detection of a nuclear attack from a submarine. A small hydrogen bomb is set off in the canister which emits penetrating radiation that creates X-rays and a destructive shock within the missile canister. The X-rays are aimed at enemy warheads by numerous small rods before the weapon destroys itself. The drawbacks of this concept include the fact that it requires a nuclear explosion, that it must be launched to be used, and that it is a one time shot at several targets.

Particle beams have several advantages over lasers for use in space. First, they have no sensitive optics because they are focused by magnets not mirrors. Secondly, the beam is generated by a durable accelerator which, along with the magnets, are impervious to high radiation levels. Additionally, the beams are more powerful and penetrate deep into targets. But particle beams will not penetrate past 100 km of atmosphere and are thus not effective for boost phase intercepts. Most of the work with particle beams for weapons uses a "neutral beam" or a stream of hydrogen ions whose charge is stripped away as the stream of particles is accelerated. However, these weapons are bulky, heavy, power hungry, and hard to aim. Charged-particle beams use

the same concept and have only been used in limited research applications. Charged-particle have the distinct disadvantage of being bent or twisted by the earth's magnetic field.

Kinetic-energy weapons or kinetic kill vehicles (KKV) could be used in all phases of ballistic missile interception and work by hitting a missile with high-speed projectiles. The course of the projectile is not affected by the atmosphere or magnetic fields and they do not diverge like lasers do. However, they do require electronic guidance and maneuverability so that they can home in on their targets. The rocket KKV concept was tested in June 1984 during the Army's Homing Overlay Experiment (HOE) when a high-speed rocket used long wave infrared sensors to home in on and successfully destroyed a dummy ICBM warhead fired from over 4000 miles away. Seconds before impacting at a closing speed of over 20,000 mph, the interceptor unfurled a 15 foot metal umbrella net to increase the destructive radius. Electromagnetic rail guns make use of smaller (3 grams - 3 kilograms) projectiles or "smart bullets" that also rely on electronic homing to ensure a final hit. The rail guns, a favorite of some SDI researchers, are like high tech rifles that accelerate projectiles down a barrel 25 meters long and almost a foot in diameter through the use of electromagnetic forces. The greatest projectile speed has been 11 km/s for a 3 gram plastic bullet. The goal is to fire 3 to 5 gram bullets at speeds of 20 to 30 km/s. However, improvements in structural materials, speed, and size of guns and bullet guidance systems is needed to enhance the feasibility of

these systems.

TECHNOLOGIES

There are many emerging technologies, not directly related to SDI, that may enhance the feasibility of strategic defense. Computing, microprocessing, and software application represent critical technologies for SDI. Improvements in speed, capacity, and survivability are needed in this area. Research into Very High Speed Integrated Circuits (VHSIC) may provide an order of magnitude increase in computational ability, use only twenty percent of the power now required, be one-fourth the size and weight, cost one-tenth of what circuits now cost, and be at least ten times faster.¹⁸

With up to 10 million lines of code needed for a battle management/command, control, and communications (BM/C³) of a multilayered system the programming and testing requirements of such a system are enormous and require improvements in automated programming techniques.¹⁹ Artificial Intelligence (AI) technology also has the potential to unlock some of doors in

18. Marsh, "A Preview of the Technology Revolution", Air Force Magazine, August 1984, p. 44.

19. Fletcher, "The Technologies for Ballistic Missile Defense", Issues in Science and Technology, Fall 1984, p. 25.

BM/C³ logic and decision making. The Defense Department plans to build the SDI system's battle management/command, control, and communications in a "transparent" manner in order to incorporate future improvements in software and microprocessing. A major challenge is to ensure that the BM/C³ system can continue to function in an intense nuclear environment. Hardening against electromagnetic pulse (EMP) radiation is an integral part of the program and research into gallium arsenide is viewed with high hopes for improved survivability.

Power source technology is another critical area for SDI research. Two issues have dominated current power and power conversion discussions; 1. Technical feasibility of prime-power and pulse-power sub systems and their packaging for spaced based SDI systems, and 2. Advances needed in the state of the art to provide ground based power.²⁰ There are three main categories of power requirements; baseload, alert mode, and burst mode. Baseload, or "housekeeping" power, is needed continuously for up to seven years at the few hundred kilowatt level to maintain surveillance, acquisition, and tracking functions. Alert mode power, in the 1 to 2 megawatt range, would be needed for extended periods of time, possibly up to a year. The burst mode power would require short periods (10-300 seconds) of 100 or more

20. Greeley, "SDIO Emphasizes Research On Improved Power Sources", Aviation Week and Space Technology, March 17, 1986, p.74

megawatts to power the weapon systems envisioned. Figure 10 shows the current time/power relationships of many potential power sources.²¹ From this chart it is evident that nuclear reactors have the best potential for space-based power requirements. The SP-100 space nuclear reactor program, jointly sponsored by SDIO, NASA, and the Energy Department, has completed technology assessment and General Electric has been selected to conduct Phase 2 research of the out-of-core thermoelectric converter for the fast-spectrum, liquid-metal-cooled reactor used in ground testing.²² The largest on-board power supply ever sent up to space was the solar cell array on Skylab in 1973 that pumped up to 12 kilowatts continuously.

Another important technological shortfall is our present launch capability. With the Challenger tragedy and the recent loss of Titan 34D and Delta missiles our ability to place weapon systems in space is severely limited. Testing, or actually deploying and maintaining, a SDI system could require dramatic increases in launch vehicles. Research into a trans-atmospheric vehicle (TAV) may provide some long-term relief. However, many of the sensors and weapons will need to be placed in geosynchronous orbits or even in deep space, well beyond a low earth orbit capability of

21. "SDI: The Grand Experiment", IEEE Spectrum, September 1985, p.54.

22. Greeley, "SDIO Emphasizes Research On Improved Power Sources", Aviation Week and Space Technology, March 17, 1986, p.74

the shuttle or TAV.

Probably the most important areas that needs reevaluation due to improvements in technology are strategy, doctrine, and organization. While these areas go hand in hand with battle management/command, control, and communications they encompass a broader look at our national strategy and how we will deter war and, if necessary, how we will defend ourselves against a nuclear attack. Technology will soon outpace our defense strategy, doctrine, and military organization. Changes in these areas must be part of the foundation of a strategic defense architecture.

IMPORTANT STRATEGIC DEFENSE SYSTEM PRINCIPLES

A strategic defense architecture must incorporate certain features or principles in order to be an effective defensive system in the next decade. The system must be:

1. Reliable: The SDI system must be reliable enough to interject a level of uncertainty into a potential attacker's mind in order to be a credible deterrent.
2. Survivable: A very big question remains as to the survivability of a spaced-based system given the current Soviet lead in anti-satellite (ASAT) capability. While no mix of space and ground-based systems has been determined, it is obvious that the entire system must be capable of

repelling a preemptive disabling strike and remain operational in the "heat of battle".

3. Secure: Security is of paramount importance. Sophisticated Soviet "hackers" can not have access to the sensor, tracking, intercept, and control algorithms or they will be able to devise countermeasures or, even worse, turn the system against the U.S.
4. Safe: The system must be safe to the world population. This not only means that the system should destroy warheads not people, but both ground and space-based systems should be free of the potential for catastrophic accidents.
5. Redundant: A SDI system should have redundant capabilities to ensure its operational status during the repair and upgrade of components. More importantly, the system should be able to tolerate the disabling of a certain portion of the system without disabling the entire system. The multilayered defense or "defense-in-depth" concept is based on the principle of redundancy. One concept which is receiving some attention is the "swarm" option where large numbers of smaller, less expensive sensing, tracking, and/or weapons satellites are placed in orbit creating a huge redundant system which would be almost impossible to disable.
6. Modular: By dividing the system up into smaller modules of

technology the system can be deployed incrementally as technologies reach operational status. Also, the system can be deployed in modules with varying degrees of protection for our allies. Many of the sophisticated tasks including software programming, program debugging, and missile tracking may best be accomplished by dividing the task into manageable components that are then deployed incrementally.

7. Fault-tolerant: The SDI undertaking is a huge technical task probably requiring more than 10 million lines of programming code.²³ Present capabilities do not even permit writing such extensive software much less assuring that it is error-free. Any large system will have its share of bugs. However, the system must tolerate a reasonable number of errors and rely on other elements of the system to be self-correcting.

8. Instantaneous: The nature of modern "Star Wars" battle will be such that decisions will have to be made ahead of time. There will not be time for a presentation of the options prior to making a command decision. The operational control of the modules will have to be given to module commanders with the "go ahead" approval provided from the

23. Fletcher, "The Technologies for Ballistic Missile Defense", Issues in Science and Technology, Fall 1984, p. 25.

national command authorities. Most of the decision can be programmed into the software, with the only active decisions required for overrides.

9. Flexible: A SDI system can not only limit us to a narrow set of options, it must be flexible enough to fit the world situation. This does not negate the above mentioned instantaneous principle, rather it complements it. This is to say that a flexible response is possible with the pre-programmed capabilities and intents of the strategic defense system tied to the desired response. This may be accomplished by tying the response of the system to different alert or status levels such as Defense Condition (DEFCON) levels.
10. Durable: Many of the space-borne components of the SDI system will have to maintain continuous alert status for many years. These components must be protected from environmental factors in space and must have power sources which last for reasonable amounts of time
11. Versatile: The deployed system must provide for the ability to expand its capability to cover more threats than just the one posed by the ballistic missile. Technology is changing the nature of the threat and the SDI architecture must accommodate upgrades in order to achieve true strategic defense.

TRUE STRATEGIC DEFENSE

Almost all of the material published on SDI research deals with ballistic missile defense. However, when contemplating the design of a system architecture it is essential to consider the next generation of threats. This would include advanced ballistic missiles and warheads as well as other delivery vehicles. Air breathing delivery vehicles (cruise missiles, remotely piloted vehicles [RPVs], and manned aircraft) represent a very real threat now and their significance in the offensive nuclear environment is only likely to increase. Stealth or low radar observable technology will make many of our current anti-aircraft detection systems obsolete. A much more serious threat comes from high speed, terrain-following, nuclear cruise missiles which can be launched from submarines, aircraft at stand off range, or from enemy territory. Current SDI intercept scenarios focus primarily on the ballistic missile trajectory and characteristics. While this may be an essential part of the initial system, prudent planning requires an architecture that accommodates interception of other delivery mechanisms. Many of the interception weapons and battle management tools can be used to combat the air breathing threat, but the surveillance, acquisition, detection, discrimination, and tracking may have to be different. While ballistic missile defense occupies center

stage in the current research programs and national debate, any deployed system must be able to accommodate the expansion of the system to include air breathing defense.

PROPOSED SYSTEM ARCHITECTURE

Part of the original task of this report was to develop a proposed SDI system architecture. Research for this report amplified the difficulty in such a task. However, some ideas that may be useful have evolved from the months of review of the published research. A viable SDI architecture may likely have some of the following features:

- The architecture will be built around sophisticated artificial intelligence software systems to control the battle management/command, control, and communications.
- The system will have several modes of operation tied to the DEFCON status. These modes will include: continuous surveillance, alert, increased alert, active defense, testing, and modular control by field commanders. Each mode will only permit certain defensive options based on pre-determined and pre-programmed scenarios unless options are actively released by national command authority to the field commanders.
- All system components and defensive layers will have a

common, abbreviated, computer coding system to identify all objects that may be potential threats. Once identified a complete object history and status will be recorded, monitored and exchanged between components.

- Software programming will use self-programming AI techniques to duplicate related programming tasks. Testing will also be accomplished with the aid of AI technology.
- Continuous surveillance of the entire earth will initially be provided by an array of 24 geosynchronous satellites supplemented by increasing numbers of sensors in low earth orbit and random deep space sensors.
- Object positioning and velocity data will be integrated with the national global positioning system.
- The system will be deployed and operated modularly. Modules will be relatively small and related to geographic defense positions on the earth.
- The system will emphasize a multilayered approach. The first layer to be developed for deployment should be midcourse interception based on the early success of the HOE experiment and on the relative ease of boost phase countermeasures. This system will probably use a constellation of kinetic kill vehicles in low earth orbit. The system could take the form of 1,000 launchers each

carrying three separate homing interceptors.²⁴ This will evolve into a "swarm" defense as the price of KKV battle stations decreases.

- Power for space-based sensor, surveillance, and tracking satellites will be solar. Battle stations will be powered by nuclear reactors similar, but much smaller and lighter, to nuclear reactors on naval vessels.
- Post-boost phase defense will be absorbed into the midcourse phase method of interception.
- Terminal defense systems will play an increasingly important role and should be the second layer developed. Laser systems may be appropriate for the terminal phase in order to overcome the atmospheric effects. Sophisticated ground-based infrared, motion, and Doppler radar systems will be used in conjunction with space-based sensors to detect ballistic and air breathing threats in this phase. The terminal phase will provide the primary protection against the air breathing threat.
- Space-based sensors and weapons will incorporate their own defenses against ASAT weapons.
- The defense system will incorporate ASAT capabilities in

24. "Mid-Course ABM Defense Recommended", Aviation Week and Space Technology, October 29, 1984, p. 23.

addition to missile and air breathing defense.

- The "pop-up" concept will not be used because of the objection to using nuclear weapons for nuclear defense, the limited flexibility of such a defense, and improvements in anti-submarine capabilities.
- Airborne sensors, weapons and BM/C³ functions will be an integral component of the system particularly for the terminal phase. As trans-atmospheric vehicle technology develops ground-launched, retrievable, spacecraft will take over this function.
- A limited boost-phase capability will take a low priority and, if deployed, should only be deployed against designed high probability launch areas.

While this list of possible features of a SDI architecture is far from complete, it provides some speculation as to what such a system may look like and how it will evolve.

CONCLUSION

As Dr. Fletcher states, "The current [SDI] research program is designed to demonstrate affordable technologies capable of handling an expanded Soviet offensive force. Until this work is complete, any 'systems analyses' will be conjecture at best."

The purpose of these paper is not to do what large numbers of scientists and national leaders with large staffs and budgets have been unable to do over the last 3 years of SDI research. Rather, it was to outline the direction of strategic defense research and discuss the principles that are key to the development of a SDI architecture. The rough sketch of one possible architecture provided in this report is far from definitive and only serves to illustrate the difficulties encountered when creating an architecture for large, sophisticated systems.

There are clearly many uncertainties if the United States were to embark on the path to developing a strategic defense system. The present state of technology does not permit us to confidently construct an effective ballistic missile defense, but "we have not been presented with any compelling technical reasons that show that such defenses are not possible."²⁵ Continued research is probably a prudent course. The key step in continued research is the formulation of a system architecture in which component technologies can develop and integrate into a comprehensive system.

Some contend that successful defensive technologies will offer new opportunities for strengthening deterrence and new

25. Fletcher, "The Technologies for Ballistic Missile Defense", Issues in Science and Technology, Fall 1984, p. 29.

possibilities for arms limitation. The larger question then becomes one of defense strategy, doctrine, and national policy and priorities.

SOVIET OFFENSE:

1400 MIRVed ICBMs x 10 warheads per missile = 14,000 warheads

14,000 warheads x 10 decoys per warhead = 140,000 decoys

1400 warheads + 140,000 decoys = 154,000 objects to be tracked

REQUIRED U.S. DEFENSE:

Level	Effectiveness	Cumulative Effectiveness	Warheads Missed	Decoys Missed
1	.90	90%	140	1400
2	.90	99%	14	140
3	.90	99.9%	1.4	14
4	.90	99.99%	.14	1.4
<hr/>				
1	.70	70%	420	4200
2	.70	91%	126	1260
3	.70	97.3%	37.8	378
4	.70	99.19%	11.34	113.4

Source: "Technical Issues for Strategic Defense Initiative",
Stephen Rockwood, International Peace Research Institute
Conference, Stockholm, Sweden, July 5-7, 1985 as reported
by "SDI: The Grand Experiment", IEEE SPECTRUM, September
1985, p.45.

FIGURE 1. POSSIBLE STRATEGIC DEFENSE SCENARIO CALCULATIONS

Fifteen major SDI experiments

Project name	Goal	Primary contractors	Target date
Alpha; large optics demonstration experiment (LODE); large advanced mirror program (LAMP)	Demonstrate beam control of chemical laser using one-third-size model space laser	TRW, Lockheed, ITEK, respectively	Late 1980s
Acquisition, tracking, and pointing program (ATP)	Demonstrate tracking technologies for ground- and space-based weapons and surveillance; may track ballistic missile booster plumes from shuttle	Lockheed	Early 1990s
White Sands Missile Range ground-based test using mid-infrared advanced chemical laser	Integrate laser and optical subsystems for ground tests	TRW	Not announced
Ground-based laser uplink experiment	Excimer and free-electron lasers will be demonstrated and integrated with a beam director in space	Not announced	Not announced
Boost surveillance and tracking system (BSTS)	Conduct a "near real-time fully responsive" experiment that may measure the signature of booster plumes	General Electric, Grumman, TRW, Lockheed (definition studies)	1991
Space surveillance and tracking system (SSTS)	Demonstrate survivable space system for mid-course surveillance	Rockwell International, TRW, Lockheed (definition studies)	1991
Airborne optical adjunct (AOA)	Demonstrate feasibility of using infrared sensor on airplane for terminal surveillance	Boeing	1988
Kinetic-kill vehicle (KKV)	Demonstrate rocket-propelled projectile launch and guidance capability from space platform; tests against ASATs possible	Rockwell International, TRW, Hughes, Martin Marietta (definition studies)	Early 1990s
Ground-based rail gun experiment	Prove capability of launching guided and unguided projectiles	Not announced	Not announced
Space-based rail gun experiment	Demonstrate rail gun in space to destroy antisatellite weapons	Not announced	Not announced
High endoatmospheric defense interceptor (HEDI)	Use kinetic-kill rockets to destroy warheads within the atmosphere	Boeing, Lockheed, McDonnell Douglas, Martin Marietta (definition studies)	Not announced
Exoatmospheric reentry vehicle interceptor subsystem (ERIS)	Use kinetic-kill rockets to destroy warheads above the atmosphere	Boeing, Lockheed, LTV Aerospace, Martin Marietta (definition studies)	Not announced
Terminal imaging radar	Develop a fixed ground-based track and imaging radar for terminal defense	Westinghouse, Raytheon	Not announced
Long-wavelength infrared (LWIR) probe	Use a ground-launched LWIR sensor to demonstrate feasibility as a pop-up terminal defense sensor	Not announced	Not announced
Terminal defense system demonstration	Use terminal imaging radar, HEDI and software systems to intercept strategic ballistic missiles in flight	Not announced	Early 1990s

Sources: Spectrum Interviews; 1985 Annual Report to Congress on the Strategic Defense Initiative; target dates from Federation of American Scientists

Source: "SDI: The Grand Experiment", IEEE Spectrum, September 1985, p.57.

FIGURE 2. Major SDI Experiments

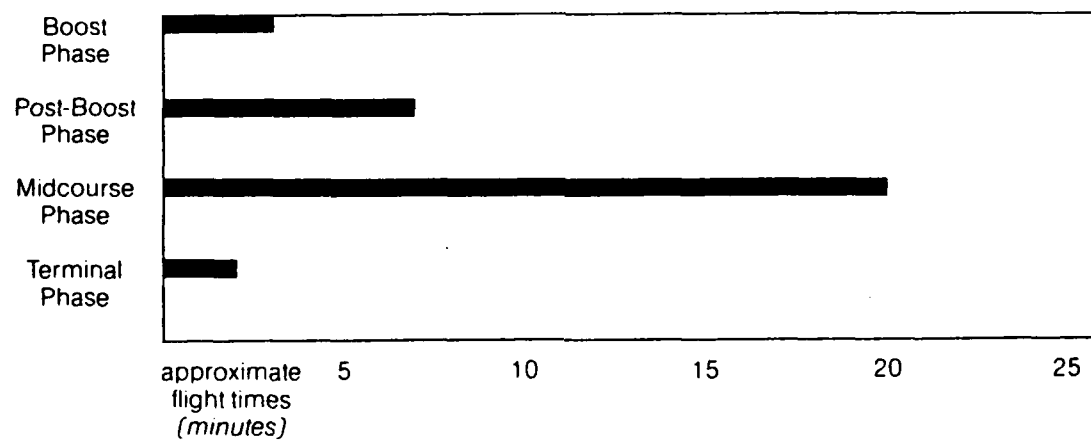
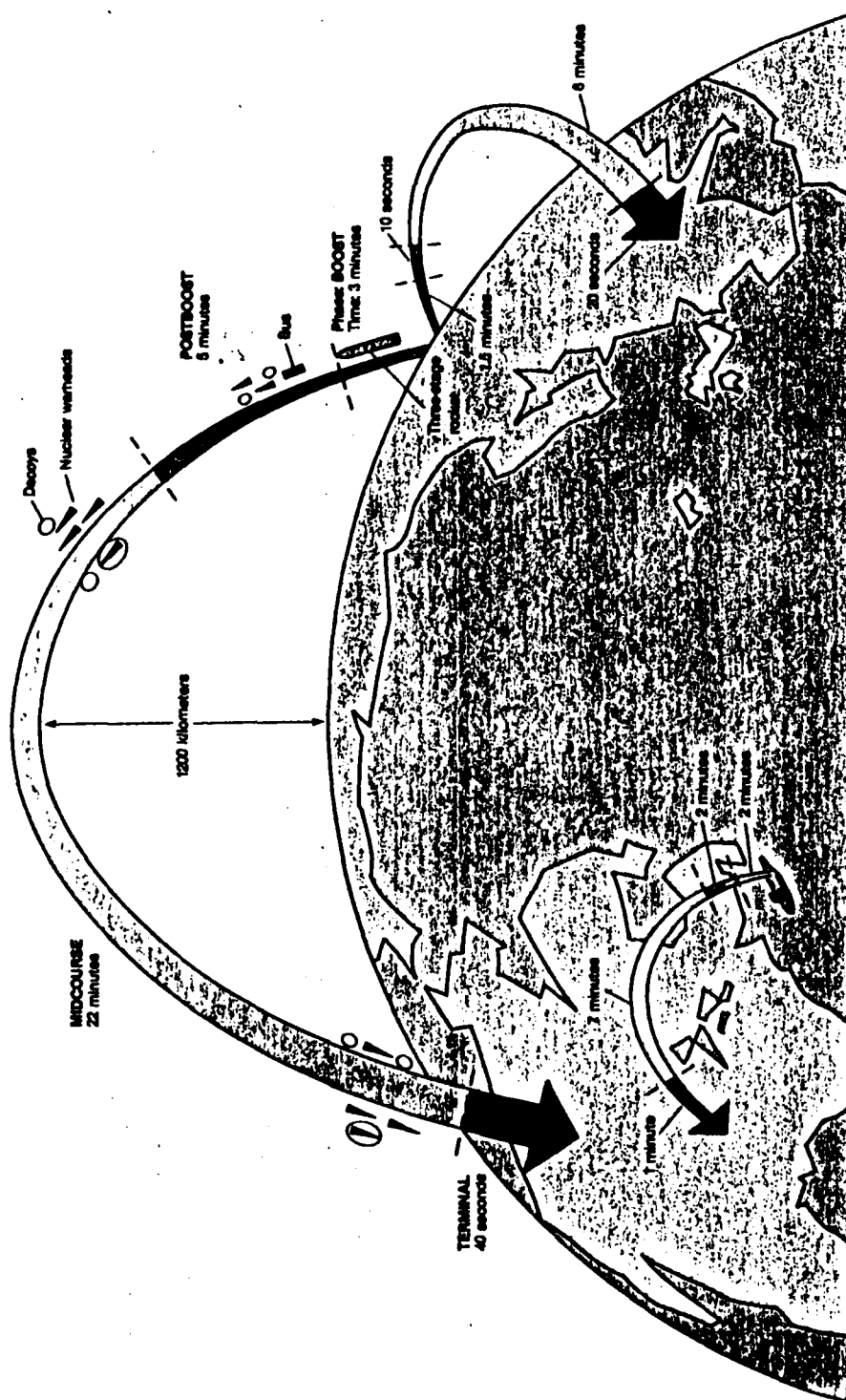


FIGURE 3. Flight Time in the Four Phases of a Ballistic Missile Trajectory

SOURCE: James C. Fletcher, "The Technologies for Ballistic Missile Defense", Issues in Science and Technology, Fall 1984.



warheads and decoys travel on ballistic trajectories, reaching as high as 1200 kilometers. As the warheads reenter the atmosphere in the brief terminal phase, they heat up and the lighter decoys slow down and burn up. The length of each phase varies. Intermediate-range ballistic missiles (arc at right) and submarine-launched missiles (arc at left) travel through the same four stages, but their terminal phases are of different durations. Fast-burn boosters could reduce the time for boost-phase interception to less than 1 minute. Similarly, by releasing warheads and decoys in "clusters," the time for postboost deployment could be lowered to 10 seconds. But the changes have penalties for the offense.

During its 31-minute intercontinental flight from the Soviet Union to the United States, a nuclear missile would go through four distinct phases. The rocket lifts off in the boost phase, burning for 3 minutes for an MX-like missile. At about 200 kilometers, the third-stage booster burns out. The missile is well beyond the earth's atmosphere and can begin to deploy its warheads and decoys from a spacecraft-like "bus" in frictionless space. During this 5-minute postboost phase, the bus uses thrusters to make small adjustments to its trajectory. After each precise adjustment it releases a warhead and perhaps tens of decoys. While in the long mid-course portion of the flight, the

Source: "SDI: The Grand Experiment", IEEE Spectrum, September 1985, p. 37.

FIGURE 4. Ballistic Missile Trajectory

COMPONENTS	ALTITUDE	DEFENSE PHASE
Battle Management Satellites	any altitude	boost, post-boost midcourse, terminal
Geosynchronous Sensor Satellites	36,000 km	boost, post-boost, midcourse, terminal
Midcourse Sensor Satellites	5,000-25,000 km	midcourse, post-boost
Laser Weapon Platforms	lower earth orbit	primarily boost, also post-boost, midcourse
Particle Beam Platforms	lower earth orbit	primarily boost, also post-boost, midcourse
Hypervelocity Gun Platforms	lower earth orbit	primarily boost, also post-boost, midcourse
Rocket Pod Platforms	lower earth orbit	primarily boost, also post-boost, midcourse
Surveillance Aircraft	15 km	terminal
Midcourse Interceptor Rockets	ground-based	midcourse
Terminal Interceptor Rockets	ground-based	terminal

Shaded: alternatives for boost phase defense

Source: James C. Fletcher, "The Technologies for Ballistic Missile Defense", Issues in Science and Technology, Fall 1984, p. 20

FIGURE 5. Likely Components of a Ballistic Missile Defense

Defensive weapons and countermeasures

ICBM phase	Defense weapon	Countermeasure ^a	Counter-countermeasure
Boost	Ground-based laser	Heat shield; reflective coating; aerosols	Increase beam energy; Increase beam intensity
	Space-based laser	Heat shield; reflective coating; aerosols	Increase beam energy; Increase beam intensity
	X-ray laser	Fast-burn booster	None
	Space-based rail gun	Fast-burn booster	None
Postboost	Space-based chemical rocket	Fast-burn booster	None
	Ground-based laser	Heat shield; reflective coating; aerosols	Increase beam energy; Increase beam intensity
	Space-based laser	Heat shield; reflective coating; aerosols	Increase beam energy; Increase beam intensity
	Space-based particle beam	Mass shielding	Increase beam energy
Mid-course	X-ray laser	Mass shielding	None
	Space-based rail gun	Decoys	Discrimination tracking
	Space-based chemical rockets	Decoys	Discrimination; tracking
Terminal	Space-based particle beam	Mass shielding	Increase beam energy
	Space-based rail gun	Decoys	Discrimination; tracking
Terminal	Ground-based rail gun	Maneuverable projectile	Homing projectile
	Ground-based chemical rockets	Maneuverable projectile	Homing projectile

^aSystem-wide countermeasures include active attacks on all weapons, decoys to fool sensors, and jamming radar to foil tracking satellites.

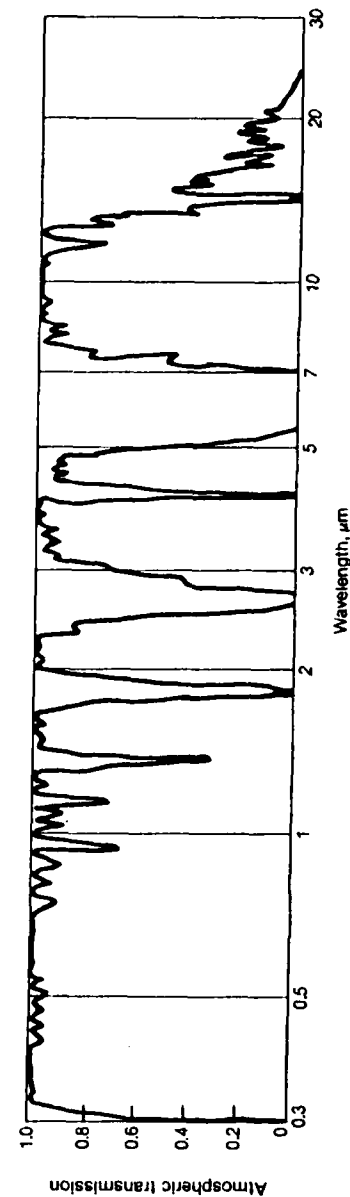
Source: "SDI: The Grand Experiment", IEEE Spectrum, September 1985, p.48

FIGURE 6. Defensive Weapons and Countermeasures

Strengths and weaknesses of weapons

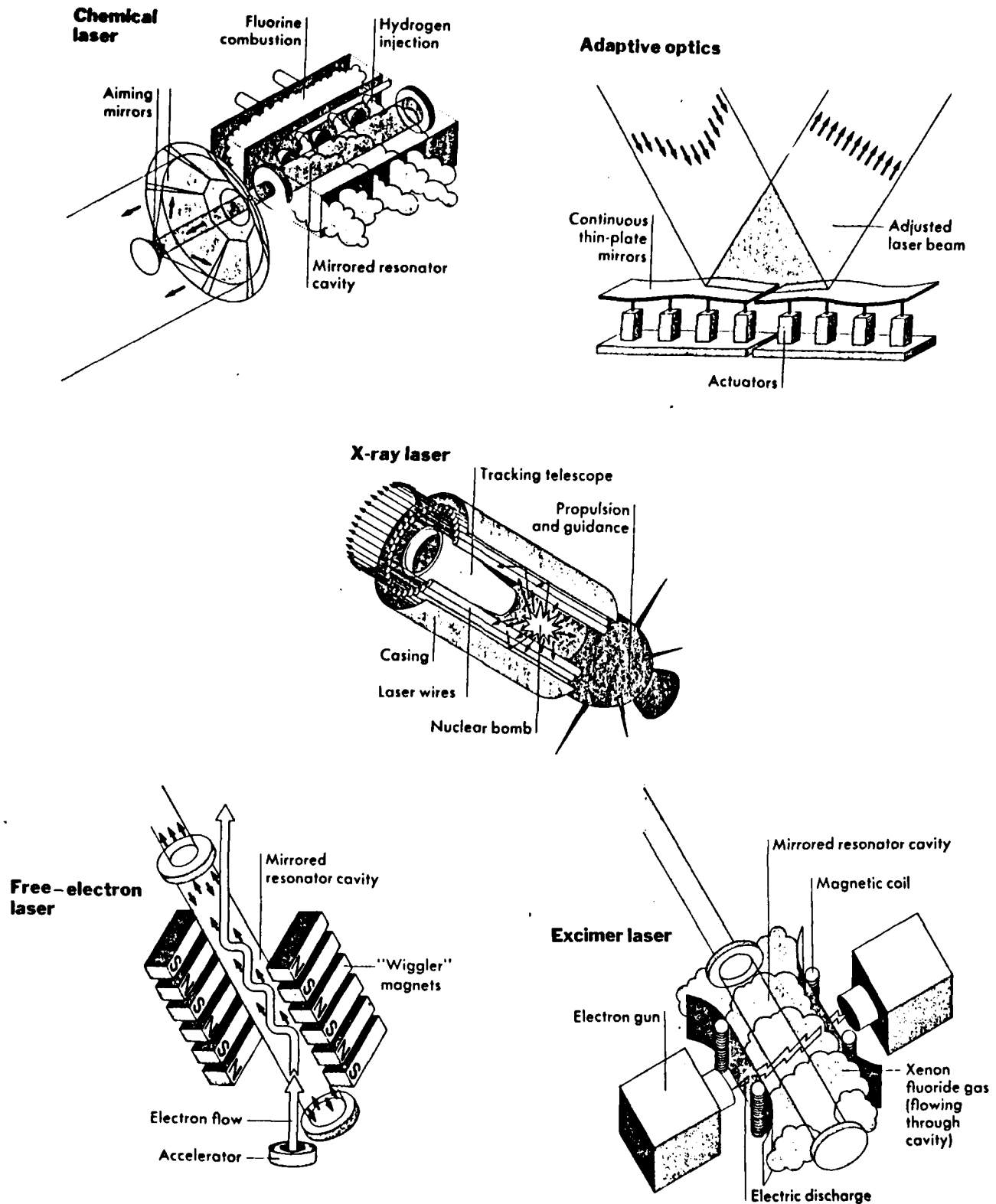
Weapon	Type	Wavelength, micrometers	Excitation mode	Power	SDI application	Strong point	Weak point
Laser	Chemical HF Iodine	2.7 1.3	Chemical reaction	Chemical	Ground-based or space-based	Speed of light; needs only small power source	Needs large optics; hard to manufacture; easy to damage
	Free-electron	Tunable from 0.1-20	Electron beam excites electrons	Electric	Ground-based	Speed of light; penetrates atmosphere	Laser destroys optical coatings
	Excimer KrF XeCl XeF	0.25 0.31 0.35	Electron beam excites gas	Electric	Ground-based	Speed of light	Inefficient power user
	X-ray	—	Lasing rods	Nuclear bomb	Pop-up	Speed of light	Must be launched
Particle beam	Neutral	—	Accelerator	Electric	Space-based	Half the speed of light; not affected by magnetic field	Stopped by atmosphere
	Charged	—	Accelerator	Electric	Space-based	Half the speed of light	Stopped by atmosphere; bent by earth's magnetic field
Kinetic	Rocket	—	—	Chemical	Ground-based or space-based	Instant kill on impact	Slow
	Rail gun	—	Linear accelerator	Electric	Ground-based or space-based	Instant kill on impact	Slow

Electromagnetic radiation of certain wavelengths is absorbed by the atmosphere (zero transmission), while other wavelengths pass through relatively unscathed (1.0 transmission).



Source: "SDI: The Grand Experiment", IEEE Spectrum, September 1985, p.49

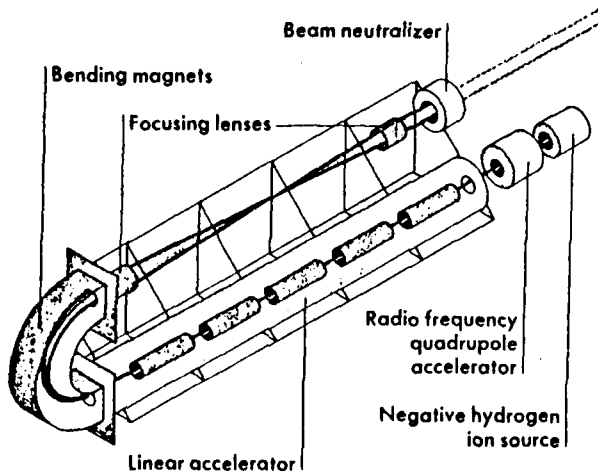
FIGURE 7. Strengths and Weaknesses of Weapons



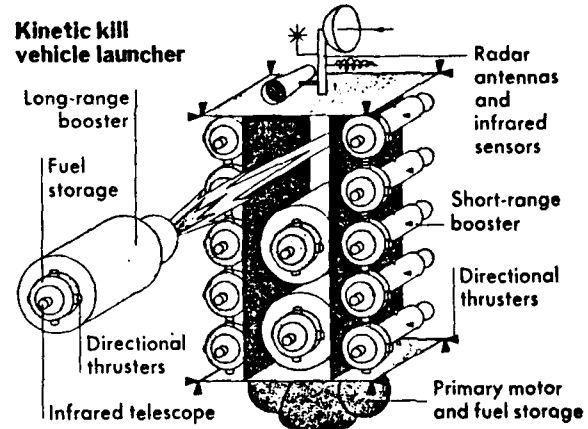
Source: "Battlegrounds in the Heavens", Discover, September 1985, pp. 52-54.

FIGURE 8. Proposed Laser Weapons

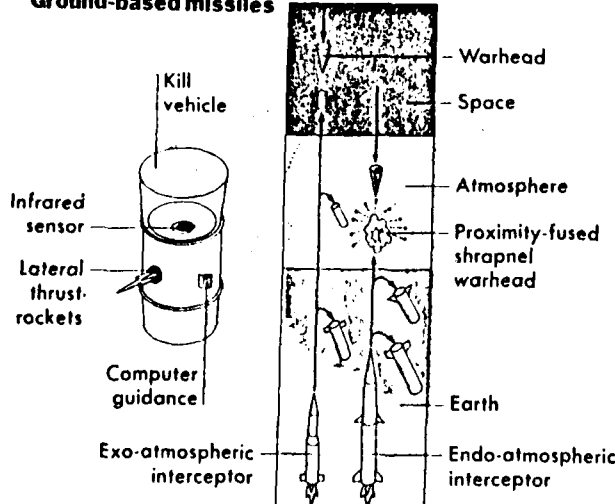
Neutral particle beam weapon



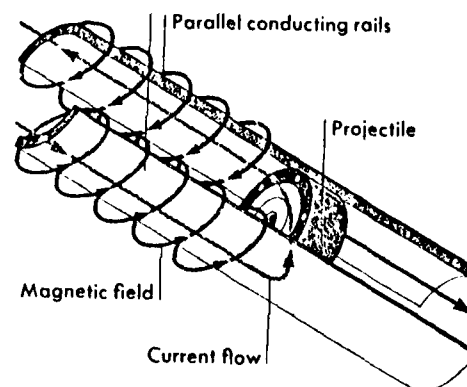
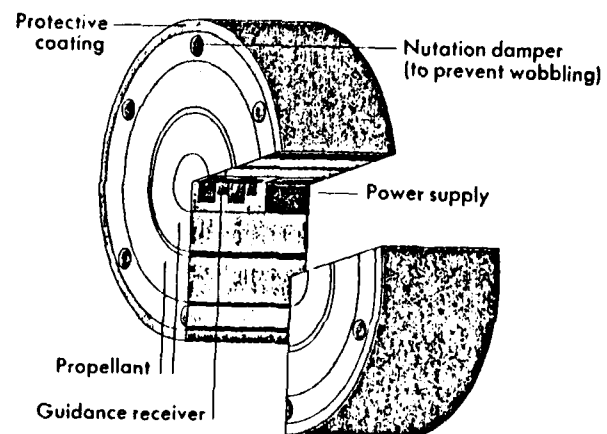
Kinetic kill vehicle launcher



Ground-based missiles

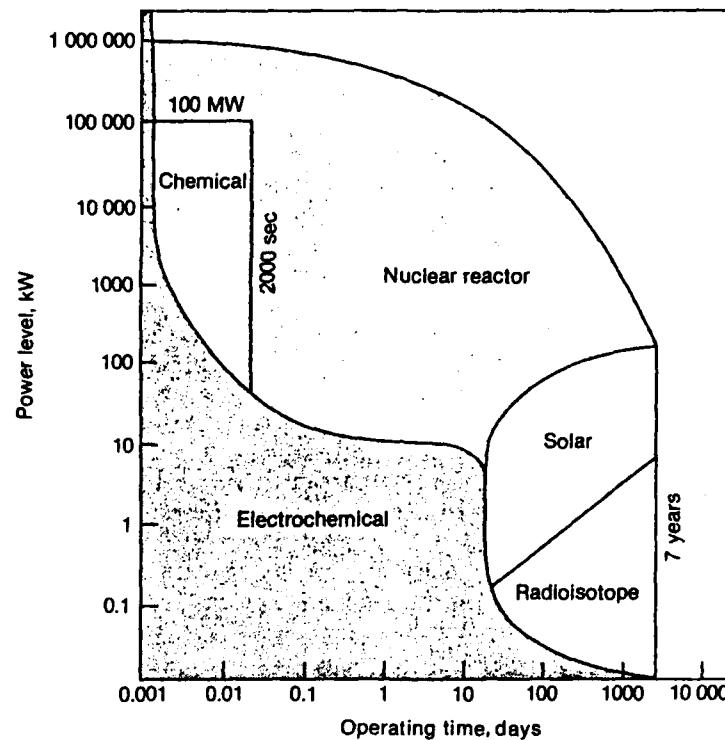


Electromagnetic projectile and launcher



Source: "Battlegrounds in the Heavens", Discover, September 1985, pp. 59-63.

FIGURE 9. Proposed Beam and Kinetic Energy Weapons



[4] Although there are many potential power supplies for space-based weapons, SDI researchers are leaning toward nuclear reactors, because weapons platforms will have to remain battle-ready for seven years (2555 days) or more. Base-load power needed to maintain systems would be 1 to 2 MW, but when they are fired weapons may require up to 300 MW, which could be provided by reactors or chemical reactions like those that fuel rockets.

Source: "SDI: The Grand Experiment", IEEE Spectrum, September 1985, p.54

FIGURE 10. Performance of Possible Power Sources

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